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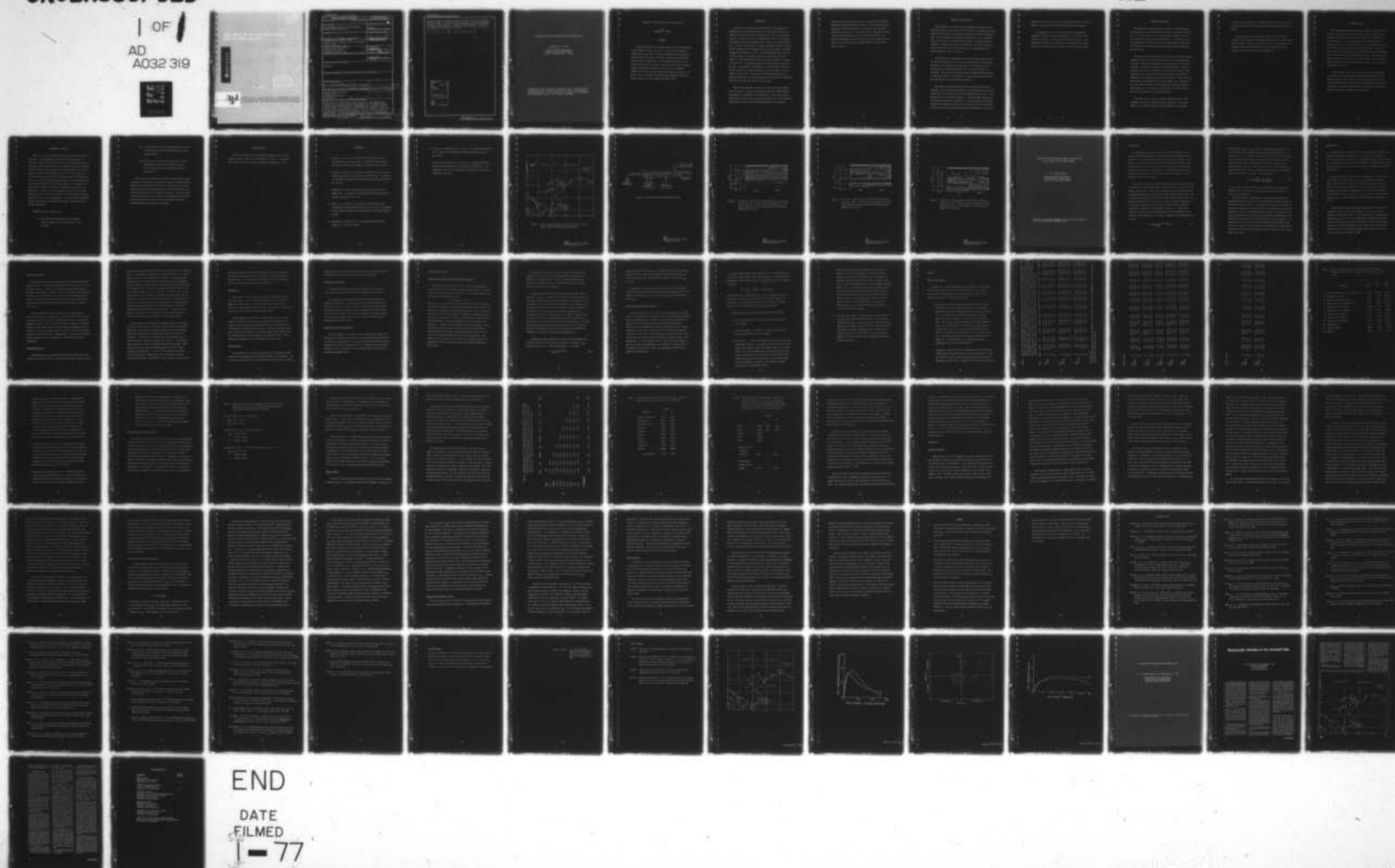

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OCTOBER 1976

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A DIVISION OF THE UNIVERSITY OF WASHINGTON

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) (6) FINAL REPORT FOR OFFICE OF NAVAL RESEARCH CONTRACT N00014-75-C-0187,	5. TYPE OF REPORT & PERIOD COVERED Final
	6. PERFORMING ORG. REPORT NUMBER --
7. AUTHOR(s) (10) Shashikant R. Shah ~~and~~ M. Jawed Hameedi	8. CONTRACT OR GRANT NUMBER(s) (15) N00014-75-C-0187 NEW
9. PERFORMING ORGANIZATION NAME AND ADDRESS Applied Physics Laboratory, Univ. of Washington 1013 N.E. 40th Seattle, Washington 98105	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Department of the Navy Arlington, Virginia 22217	12. REPORT DATE (11) October 1976
	13. NUMBER OF PAGES 77 (12) 82p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from the report).

18. SUPPLEMENTARY NOTES

This report consists of the following ~~is a compilation of three manuscripts~~: (1) Underwater Acoustic Studies of the Chukchi Sea (Published in the Proceedings of the Ultrasonics International 1975 Conference, London, 1975, p249-275); (2) Aspects of Water Column Primary Productivity in the Chukchi Sea during Summer; and (3)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

acoustic volume scattering
Chukchi Sea
biological productivity
bioacoustics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a compilation of three manuscripts. One, "Bioacoustic Studies in the Chukchi Sea," is a brief summary of the research conducted under Contract N00014-75-C-0187. Another describes the acoustic aspect of the studies in the Chukchi Sea during July 1974. Analysis of the data reveals scattering strengths as great as -60 dB (re $1/m^{-1}$) at 105 kHz, and the echograms indicated intense biological activity, at least during the summer months. The ~~third paper~~ quantitatively describes the phytoplankton

The first manuscript

second manuscript

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productivity and the related biological processes extant in the Chukchi Sea during summer. The data on selected biological, chemical and physical variables, obtained concurrently with primary productivity measurements, are statistically analyzed. In addition, factor analysis is used to investigate the covariation in the data. The third summarizes the overall contract effort and is a reprint from the Arctic Bulletin, v2 n7 p8-10 1975.

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UNDERWATER ACOUSTIC STUDIES OF THE CHUKCHI SEA

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Presented at the Ultrasonics International 1975 Conference, Imperial College, London, 24-26 March 1975. Published in the proceedings of the conference, p. 249-252 (IPC Science and Technology Press, Ltd., Surrey, England).

Underwater Acoustic Studies of the Chukchi Sea

By
Shashikant R. Shah

ABSTRACT

This paper describes the acoustic aspect of a study undertaken in the Chukchi Sea during July 1974 to (a) measure the acoustic volume scattering strength at various frequencies and (b) quantify the biological populations and obtain a relationship between them and the acoustic scattering. The measurements were made at both 60 kHz and 105 kHz using pulsed, cw, vertically directed, downward-looking echo-sounders lowered over the side of an icebreaker. Analysis of the data revealed scattering strengths as great as -60 dB (re 1 m^{-1}) at 105 kHz, and the echograms indicated intense biological activity, at least during the summer months.

INTRODUCTION

Since 1971 the Applied Physics Laboratory at the University of Washington has been actively studying the areas of the Beaufort and Chukchi Seas that are partially covered by ice, that is, the marginal ice zone. The project involves a comprehensive study of the physical oceanography of the area, coupled with a study of its acoustic properties. As part of this project, in August 1971 Moose and Shah [1] made the first quantitative measurements of the acoustic volume scattering strength in the marginal ice zone. These measurements were made with a 105-kHz pulsed, cw, vertically directed, downward-looking sonar. Analysis of the data indicated a high scattering strength, as large as -42 dB (re 1 m^{-1}), apparently evidence of high biological activity in the area. Subsequently, measurements at two frequencies, 38 kHz and 105 kHz, were made in the same general area in the summer of 1972 by Feldman and Shah [2,3]. The results of these measurements were in agreement with those of the previous work and reaffirmed our conclusions about the high biological activity of this area.

The work reported here was started in 1974 by Dr. Jawed Hameedi and me as part of a larger study aimed at gaining an understanding of the bioacoustic environment in the Chukchi Sea. That study involved examining the nature of the acoustic scattering layers, their biological and physical causes, and the relationship between the ecological

parameters and the acoustic data [4]. The work required numerous simultaneous measurements of the volume reverberation, biological population, chemical composition of the water, solar radiation, salinity and temperature. This paper describes the acoustic aspect of the study and discusses some of the results obtained. The acoustic measurements were made during the month of July 1974 from the U.S. Coast Guard icebreaker BURTON ISLAND at the locations shown in Figure 1.

ACOUSTIC INSTRUMENTATION

The measurements of acoustic volume reverberation were made using 60-kHz and 105-kHz pulsed (0.6 msec pulse width), cw, vertically directed commercial echo-sounders built by Ross Laboratories (Seattle, Washington, USA). The echo-sounders were modified for operation at each frequency and were used with a two-channel Sony tape deck, a specially designed electronic interface unit, and an oscilloscope. The 60-kHz and 105-kHz electronic systems were virtually identical. A block diagram of the field equipment is shown in Figure 2.

The interface unit heterodyned the received signals down to 5 kHz for the 105-kHz system and 10 kHz for the 60-kHz system for continuous recording on one channel of the tape deck. It also allowed up to 20 dB attenuation of the received signal so it would not saturate the recording. The transmit initiation signal was conditioned and recorded on the other channel of the tape deck. Vocal comments were recorded on the same channel as the synchronization pulses.

The narrow-beam transducers were used for both transmission and reception. The transducer beam patterns, and transmitting and receiving sensitivities, were measured prior to our departure for the Arctic. The beam pattern of the 105-kHz transducer is a circular cone, whereas that of the 60-kHz transducer is elliptical. The beam pattern of the 60-kHz transducer was measured along its major and minor axes, and the present results were calculated on the basis of these measurements. We are now

measuring the 60-kHz beam pattern at intermediate angles in order to obtain a better value for the effective insonified solid angle.

The equipment was set up in the icebreaker's oceanographic laboratory amidships on the starboard side. A long cable on the transducer allowed us to lower it about 2 m into the water. The measurements obtained in the upper 10 m of the ocean were invalid because of interference from the ship's hull and from the surface.

ACOUSTIC MEASUREMENTS

The measurements were generally made along a line perpendicular to an ice edge. Several locations were chosen: the ice edge boundary, and 1, 2, 5 and 10 miles (1.5, 3, 8 and 16 km) on either side of it. At each station, the ship would stop and drift. In addition to acoustic measurements and salinity-temperature-depth profiles, biological net samples were obtained whenever possible to identify and quantify the zooplankton.

The acoustic measurements were taken by first lowering the 60-kHz transducer into the water and recording a data file for approximately 10 minutes. The 60-kHz transducer was then replaced with the 105-kHz transducer and data were recorded for another 10 minutes. Prior to recording each file, a calibration circuit introduced a fixed, known voltage (50 μV or 100 μV rms) for 60 seconds at the input from the transducer, simultaneously disabling the transmitter. Thus, the time-varied gain was recorded directly on the magnetic tape, eliminating the need to know the gains of the receiver, the interface amplifier and the tape unit. The acoustic transmit power and pulse width, and the receiving sensitivity, were still required.

The ship's drift moved the transducer through the water, thus providing scanning of a greater volume of water [5]. At a typical speed to 1 kn, the ship would drift about 1000 ft (300 m) during a

10-minute acoustic data file. This was quite desirable, as the drift averaged out small-scale local variations in the concentration of the biomass.

The roll of the ship caused the transducer to rise and fall slightly in the water, with consequent small deviations in both azimuth and tilt angles. However, the period of roll was long compared to the average transmission time during each ping; therefore the errors produced by the surging motion are negligible [6].

DATA ANALYSIS

The volume scattering strength versus depth was calculated from the data recorded on magnetic tape using a digital averaging method developed at the University of Washington under the Washington Sea Grant Program [7]. In this method, the sampled envelope of the returned signal is squared and integrated over an ensemble of returns. The integrated squared envelope is scaled to obtain an estimate of the volume scattering strength of a cubic metre in numerous contiguous but non-overlapping layers of arbitrary thickness. (The volume scattering strength of a cubic metre is 10 log A, where A is the differential cross section for backscattering per cubic metre. Its units are decibels re 1 m^{-1}.)

A fixed interval of 5 m was chosen to facilitate data analysis. A few files were analyzed using intervals that coincided with the scattering layers, and a comparison of these results with the scattering obtained using the fixed-interval method showed insignificant differences. The scattering strengths presented here for each data file all represent an average of over 500 pings.

DISCUSSION OF RESULTS

Figures 3, 4 and 5 are representative of the results obtained in the study. Each graph shows the volume scattering strength as a function of depth at 60 kHz and 105 kHz, with corresponding echograms. In Figure 3, both frequencies show a dense scattering layer extending from the surface to approximately 30 m; the data taken at 105 kHz also indicate a diffuse layer between 30 m and 40 m. In the upper 30 m, the scattering strength at 105 kHz is higher than that at 60 kHz by 8 to 15 dB. In Figure 4, both frequencies show a dense scattering layer and a layer distinctly revealing single targets. In the upper 30 m the scattering strength at 105 kHz is higher than that at 60 kHz by about 10 dB. Figure 5 is rather interesting because the scattering strength at 105 kHz stays on the order of -70 dB throughout the water column and does not vary significantly. Note also that the variations between the scattering strengths at each depth interval are similar at both frequencies.

Preliminary results indicate that:

(1) The volume scattering strength in the Chukchi Sea is as high as -60 dB at 105 kHz and -74 dB at 60 kHz.

(2) In most locations, the scattering strength at 105 kHz is higher than the scattering strength at 60 kHz by several decibels.

(3) For several groups of stations averaging 10 miles (16 km) apart, the 60-kHz measurements showed little variability in the scattering observed in the upper 25 m.

Part of the study reported here involves determining the target strength of the biological scatterers for various size distributions. Completion of that work will allow us to establish the relationship between the scattering strengths measured at the two frequencies and the observed distribution of biological scatterers. The correlation of the acoustic data with the results of the biological analysis and the relevant physical variants should significantly further our understanding of the bioacoustic environment.

ACKNOWLEDGMENTS

The research described in this paper was sponsored by the Arctic Research Programs, Office of Naval Research, U.S. Navy. I am grateful to Dr. Henry Feldman for advice and guidance throughout this study.

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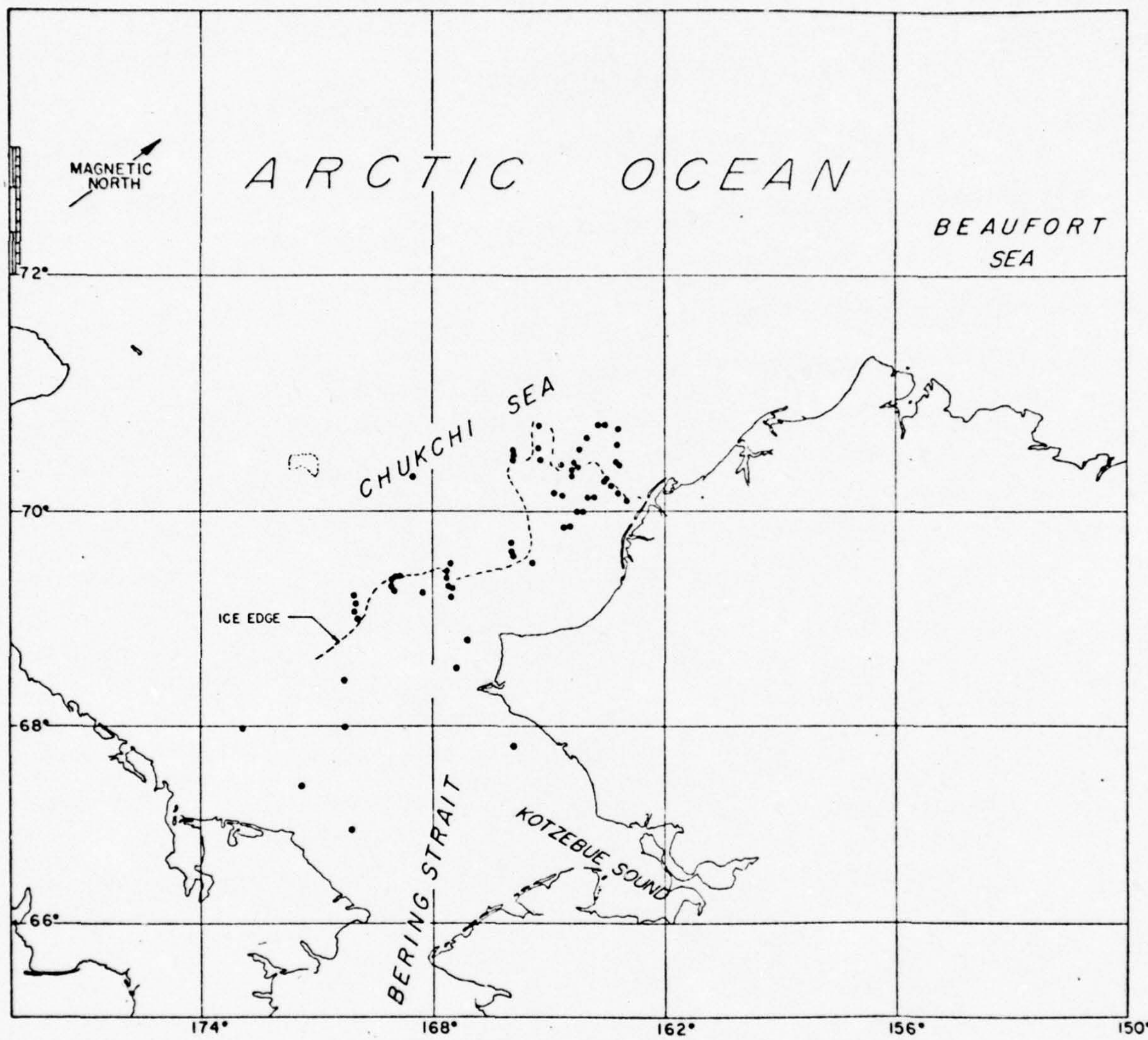

Figure 1. Map of the measurement area off the coast of Alaska.
(Dots represent locations of measurements.)

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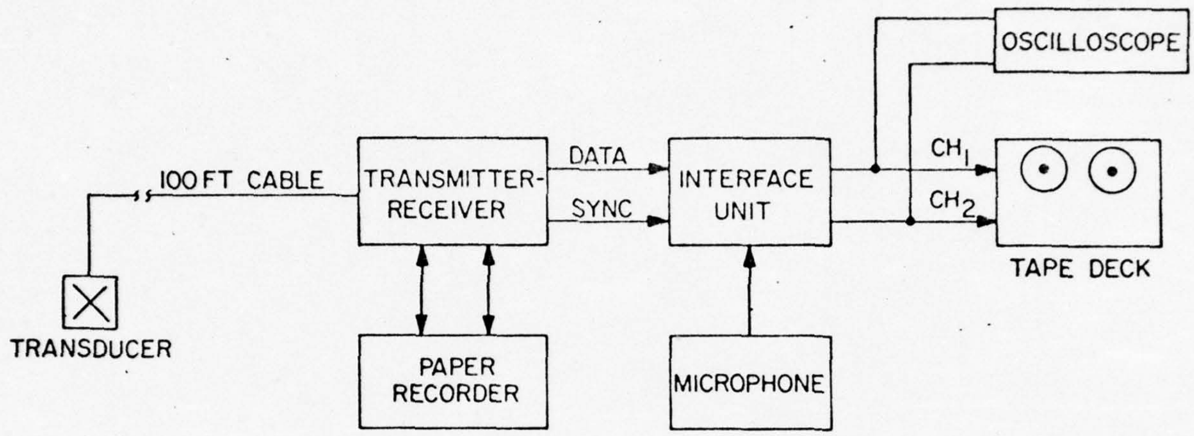

Figure 2. Volume reverberation measurement system.

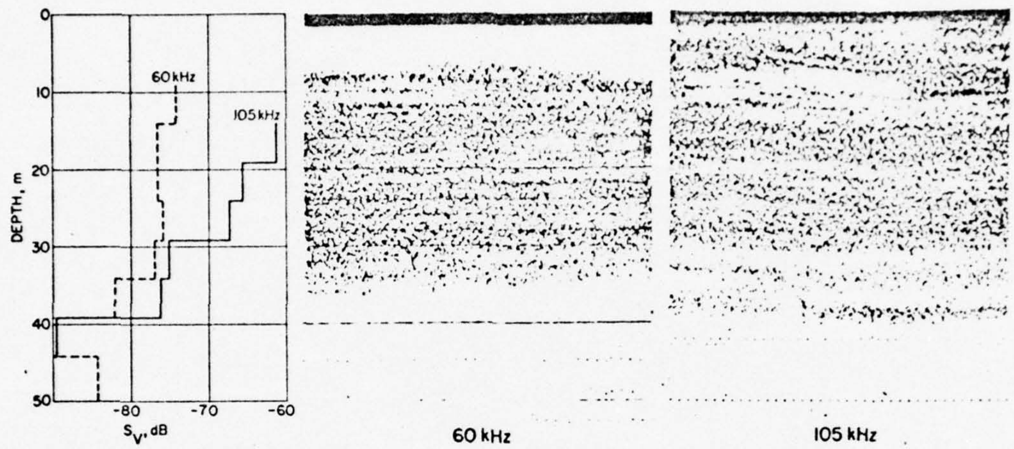

Figure 3. Station 35: Position 69°16.9'N, 169°02.8'W at 1000 hours on July 18, 1974. Volume scattering strengths as a function of depth on the left matched to the corresponding echograms on the right.

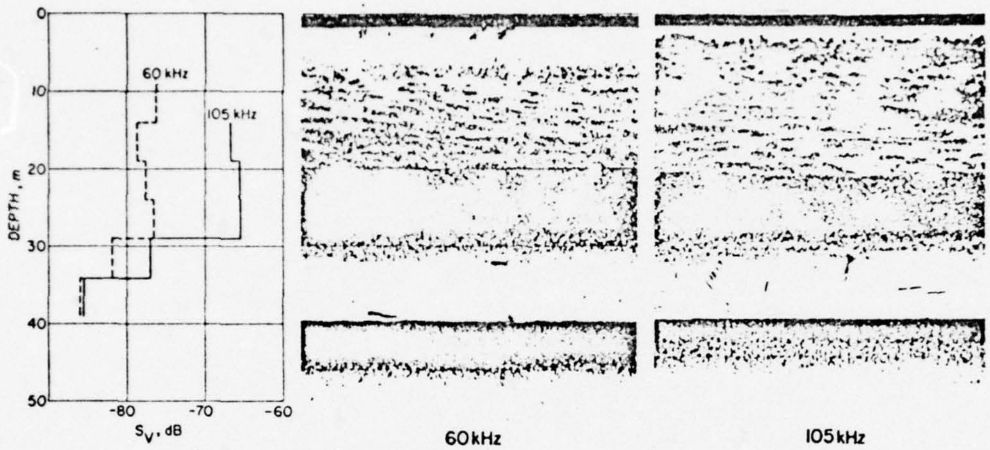

Figure 4. Station 72: Position 70°11'N, 164°26.8'W at 1100 hours on July 21, 1974. Volume scattering strengths as a function of depth on the left matched to the corresponding echograms on the right.

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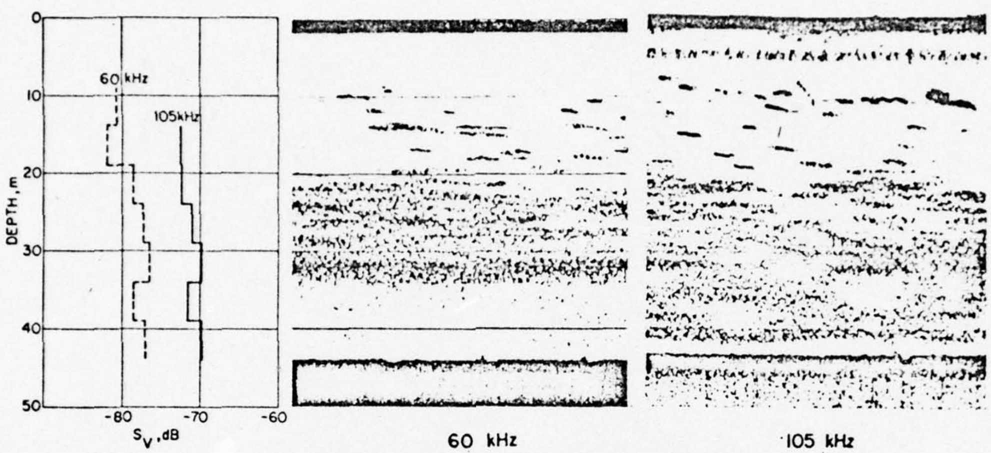

Figure 5. Station 78: Position 68°49'N, 167°06.2'W at 1300 hours on July 23, 1974. Volume scattering strengths as a function of depth on the left matched to the corresponding echograms on the right.

ASPECTS OF WATER COLUMN PRIMARY PRODUCTIVITY IN THE CHUKCHI SEA DURING SUMMER

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Submitted to Marine Biology, International Journal on Life in Oceans and Coastal Waters

INTRODUCTION

The Applied Physics Laboratory, University of Washington, has been engaged in various hydrographic and acoustic studies of the Chukchi Sea since 1971. The research presented herein is based on a part of a study aimed at the quantitative evaluation of the biological and acoustic data obtained from this area. The objectives and an outline of this project are described by Hameedi and Shah (1975). This paper deals specifically with primary production and photosynthesis-light relationships of phytoplankton in this area in summer.

The effect of light on photosynthesis by phytoplankton has been studied by Vollenweider (1965), Steele (1962), Ryther and Yentsch (1957), and Smith (1936), among others. These authors attempted to observe general patterns in light-photosynthesis relationships and expressed the results in the form of simplified mathematical expressions. Their studies indicate that, in general, photosynthesis at low light intensities increases linearly with an increase in the amount of light until a maximum level is attained, beyond which inhibition of photosynthesis takes place. Steele (1962) proposed the following relationship between the light intensity, I, and the rate of photosynthesis, P, for natural communities of phytoplankton in the sea:

$$P = P_{max} \frac{I}{I_{max}} e^{(I - I/I_{max})} . \qquad (1)$$

The parameters, P_{max} and I_{max}, represent the maximum photosynthetic rate and the optimal light intensity for the maximum photosynthetic rate, respectively. This equation, mainly because of its simplicity, has been used in several recent studies on the dynamics of the plankton primary productivity in the sea (for example, Hameedi, 1974; Taguchi, 1972). Another general equation, a modification of Smith's (1936) formula proposed by Vollenweider (1965), has primarily been applied to limnological studies (for example, Fee, 1973). In this equation,

$$P = P_{max} \frac{\underset{\sim}{a}I}{\sqrt{1+(\underset{\sim}{a}I)^2}} \cdot \frac{1}{\left[\sqrt{1+(\alpha I)^2}\right]^{\underset{\sim}{n}}} \quad (2)$$

I is the light intensity, and P_{max}, which describes the maximum photosynthetic rate (not identical to P_{max} of Smith's (1936) formula), $\underset{\sim}{a}$, α, and $\underset{\sim}{n}$ are the parameters.

The main purpose of this paper is to quantitatively describe the phytoplankton productivity and the related biological processes extant in the Chukchi Sea during summer. The results of the effect of sunlight on specific photosynthetic rate are discussed with reference to the above two equations. The data on selected biological, chemical, and physical variables, obtained concurrently with primary productivity measurements, are statistically analyzed to better understand the biological processes. In addition, factor analysis is used to investigate the covariation in the data and to rationally classify the observed variables to afford a description of the bioenvironmental regime (Van Andel and Nelissen, 1973; Fisher, 1973; Loder, 1971).

RESEARCH AREA

The Chukchi Sea is a shallow basin oriented northwest to southeast, with an average depth of about 50 m. It is usually ice-covered for seven to eight months of the year (U.S. Hydrographic Office, 1958). There is a well-defined yearly cycle of solar radiation. Summer global radiation values for Barrow, Alaska, are given by Weller and Holmgren (1974) and by Weaver (1970).

The general physical oceanography and hydrodynamics of the Chukchi Sea are not fully known. However, it is agreed that the northward water transport in the Chukchi Sea, from the Bering Sea to the Arctic Basin, is of the order of 1 million m^3/sec and is primarily due to the barotropic mode (Fleming and Heggarty, 1966). Since flow is fairly strong relative to the volume of the sea, the water masses have variable characteristics and are transitory in nature (Solomon and Garrison, in press).

High concentrations of dissolved oxygen, greater than 100% of the saturation value, have often been observed in this area in summer (Codispoti and Richards, 1971). A large variability, but generally low concentrations, have been noted for inorganic micronutrients, such as phosphate, nitrate, and silicate (Kinney *et al*., 1970). During summer, high levels of primary productivity in the water column are generally associated with the chlorophyll *a* maximum layer, usually in the lower part of the photic zone (Dawson, 1965).

MATERIALS AND METHODS

Field observations were made from on board the USCGC BURTON ISLAND during July 1974. The general sampling area and the locations of stations are shown in Fig. 1. A total of 10 stations was occupied for primary productivity measurements. Stations near the ice edge had varying amounts of broken ice; at station P-9 the ice-cover was very extensive (about 7 oktas). Due to the ship's schedule and the use of cruise time by other scientific personnel on board, the choice of the location of stations was not mine.

At each station, about an hour or so before the local apparent noon, water samples were collected with modified Van Dorn PVC (polyvinyl-chloride) 6-ℓ capacity samplers. Samples were obtained at depths corresponding to 100%, 50%, 10%, and 1% of the surface illumination. Wherever possible, water samples from 0.05% of the surface illumination were also collected; at one station, samples from the 1% level could not be obtained because of insufficient depth. Sampling depth, in meters, was determined from the computed extinction coefficients, derived from Secchi disc measurements.

Primary Productivity

Primary productivity measurements were made by calculating the rate of uptake of radioactive carbon. A portion of each water sample, contained

in 125-mℓ capacity Pyrex glass bottles, was inoculated with 1 cc (approximately 2.2 microcuries) of carbon-14 as sodium bicarbonate. A large air bubble was left to ensure mixing within the bottle. Samples were then incubated in a deck incubator (made of plexiglass) from local apparent noon to midnight or sunset. Stainless steel screens (Perforated Products, Inc., Brookline, Mass.) were used to provide illumination levels of the corresponding sampling depths, i.e., 50, 10, 1 and 0.05% of the surface light intensity. The incubator was mounted on the port side of the bow of the ship. Running sea water was used to provide a stable temperature regime in the incubator; however, the temperature of the incoming water varied considerably throughout the incubation period. The incubator temperature was therefore monitored periodically. A duplicate water sample in a dark bottle was incubated with every sample to provide a correction for dark uptake of inorganic carbon by phytoplankton.

After incubation, each sample was filtered through an HA Millipore filter (pore size, 0.45 μ). The filters were fumed over concentrated hydrochloric acid for about 1 minute and then placed into individual glass vials containing 10 mℓ of previously prepared scintillation "cocktail." The "cocktail" consisted of 9 mℓ of fluor base and 1 mℓ of Bio-Solv BBS-3 (Beckman Instruments, Inc., Calif.). The fluor base had a ratio of 5.0 g PPO:0.5 g dimethyl-POPOP:1000 mℓ toluene. Radioactivity counts were made by a Packard model 3310 Tri-Carb liquid scintillation spectrometer. A total of 50,000 counts or a maximum time of 100 minutes of counting was chosen to provide an adequate measure of the samples' radioactivity. After counting, all calculations

for primary productivity were made by computer processing; corrections were made for isotope effect (5%), dark bottle uptake, and counting efficiency (65%). Primary productivity values are given in milligrams of carbon assimilated per cubic meter per half-day.

Chlorophyll *a*

Two liters of the water sample were filtered through an HA Millipore filter (pore size 0.45 μ) with the addition of a small amount of magnesium carbonate powder. After filtration, unused edges of the filter were trimmed off and the filters were stored frozen in a desiccator in the dark until analysis in the laboratory ashore.

In the laboratory, each filter was ground with a plastic tissue grinder, and chlorophyll pigments were extracted in 90% acetone. The extract was centrifuged and the supernatant analyzed colorimetrically by a continuously recording spectrophotometer. Chlorophyll *a* concentration was calculated by the equation recommended by SCOR-UNESCO (UNESCO, 1966). All calculations were made by computer processing of the data. Chlorophyll *a* concentration is given in milligrams per cubic meter.

Solar Radiation

The incoming solar radiation was measured by a continuously recording Kahlsico actinograph which was mounted adjacent to the incubator. The instrument was calibrated at the National Weather Service Station, Seattle-

Tacoma Airport. Solar radiation values are given in calories per square centimeter (langleys) per half-day for the incubation period.

Inorganic Micronutrients

A small portion of each water sample, about 75 mℓ, was frozen in 120-mℓ capacity polyethylene bottles for chemical analysis ashore.

Concentrations of inorganic micronutrients were determined by a Technicon Auto-Analyzer. Analyses were made for reactive phosphate-P, reactive silicate-Si, nitrate-N, nitrite-N, and ammonium-N in sea water following the methods outlined by Strickland and Parsons (1968), except for ammonium-N for which a modification of Koroleff's indophenol method (see Slawyk and MacIsaac, 1970) was used. Nutrient data are given in milligram-atoms per cubic meter.

Temperature, Salinity and Density

Data on temperature, in degrees Celsius, and salinity, in parts per thousand, were obtained from conductivity-temperature-depth (CTD) profiles as a part of a separate project. Data for each sampling depth for primary productivity stations were provided by Dr. G. Garrison of our laboratory. Density of water, as sigma-T, for each sampling depth was obtained from standard hydrographic tables.

STATISTICAL PROCEDURES

Estimation of Parameters by Nonlinear Least Squares

The values of the parameters in Eqs. 1 and 2 were estimated by nonlinear regression using stepwise Gauss-Newton iterations. According to this procedure, if incident radiation, I, is the input variable, and Y denotes primary productivity, and

$$Y = f(I; P_1, P_2, \ldots, P_p) + \varepsilon ,$$

where $P_1, P_2, \ldots, P_p$ are the various parameters, then the sum of squares of the differences between the observed and computed values, $\Sigma(Y-f)^2$, is minimized as a function of the parameters (Hartley, 1961). To carry out the calculations for this procedure, a function is differentiated with respect to its parameters. A set of normal equations, equal to the number of parameters, is formed; the equations are then solved for the parameters. Iteration for minimizing the error sum of squares is used to obtain least square estimates (which, under the assumption that "error residuals" are normal variates with mean zero and variance σ^2, are also the maximum likelihood estimates) of the parameters. This method is a very useful one, but in the case of complex functions non-convergence of the iterative procedure has been reported (Draper and Smith, 1965).

Computations for these analyses were made by using the BMD-07R program of the Health Sciences' computing facility, University of California, Los Angeles (Dixon, 1973); a separate FORTRAN program, defining the function and its derivatives with respect to its parameters, was written for each equation.

A preliminary analysis of these data to estimate values of four parameters, P_{max}, $\underset{\sim}{a}$, α, and $\underset{\sim}{n}$, in Eq. 2 resulted in nonconvergence of the iterative process, even after 50 iterations. The value of the sum of squares oscillated widely; no stable solution, and consequently no estimates of the parameters, could be obtained. Visual inspection of the pattern of points on the plot of our data, specific primary productivity-versus solar radiation (Fig. 2), and its comparison with the family of P vs I curves presented by Fee (1973), indicated that a numerical value of unity can be assigned to the parameter $\underset{\sim}{n}$. This step considerably simplified the computational process because it reduced the number of parameters to three and the expression $1/\sqrt{1+(\alpha I)^2}$ was sufficient to indicate the inhibition of photosynthesis.

Vollenweider (1965), commenting on Steele's (1962) equation, suggested an introduction of two distinct parameters in place of I_{max}, $\underset{\sim}{a}$ and $\underset{\sim}{a}'$ (where $\underset{\sim}{a} \neq \underset{\sim}{a}'$), thereby redefining Eq. 1 as follows:

$$P = P_{max}\, \underset{\sim}{a} \cdot I \cdot e^{(1-\underset{\sim}{a}' I)}, \tag{1a}$$

where $\underset{\sim}{a}$ reflects the reciprocal of the light intensity at the intersect between the linear slope and the height of the saturation plateau; $\underset{\sim}{a}'$ is the reciprocal of the light intensity at which P is equal to P_{max}, i.e. I_{max}.

A nonlinear regression analysis was also made for this modified version (with three parameters) of Steele's (1962) equation to determine whether the estimated values of $\underset{\sim}{a}$ and $\underset{\sim}{a}'$ would support Vollenweider's modification.

Analysis of Data by Factor Analysis

Factor analysis was used to resolve into a simpler form the complex and, for the Chukchi Sea in particular, not yet fully known relationships among various environmental variables. The primary objective of this analysis was to assess gross features of the data presented here. Factors, which are mathematical constructs extracted from the original variables, can account for a large part of the variance and covariance in the data. Each factor can be considered as a dimension of the total system that can be defined by the key variables selected (Fritts, 1974). Geometrically, it can be surmised that if a set of variables defines a number of vectors (corresponding to the variables) in a space equal to the number of observations, factors can represent the same data in a space of fewer dimensions.

The basic model includes the common factors, F, accounting for the correlations among variables, and a unique factor, U, accounting for the unexplained variance (Harmon, 1967). A generalized model can be written as follows:

$$z_j = a_{j1}F_1 + a_{j2}F_2 + \ldots + a_{jm}F_m + d_jU_j \text{ ,}$$

where each of the n variables (j = 1, 2,...,n) in normalized form, z_j is described linearly by m common factors and a unique factor. The coefficients of the factors are referred to as "loadings." Further details of the factor analysis are given by Harmon (1967).

Results obtained from factor analysis include the following:

1. Mean, standard deviation, and coefficient of variation for each variable.

2. Correlation matrix. It provides a measure of intensity of association between a pair of variables.

3. Factor matrix. It shows the composition of factors in terms of the original variables. The number of common factors was determined by the number of eigenvalues greater than 1.0 (see Loder, 1971). The individual loadings beneath a factor indicate the relative contribution of a particular variable to that factor. Alternatively, the loading coefficients, when squared, represent the percentage of variance of the original variable contributing to an individual factor.

Since in factor analysis the common factor space is not dependent on a frame of reference, an infinite number of rotations (from one set of coordinate axes to another) are possible. Mathematical rotation of axes, in general, clarifies a factor's composition in terms of the original variables (Loder, 1971). According to Harmon (1967), rotation by the varimax method affords a parsimonious and simple solution. The varimax method has also been found to give consistent results, independent of the factoring techniques employed (Fisher, 1971). In the rotated matrix, each factor is composed of one or more variables with high loadings and the remainder with low loadings.

4. Plots of factor scores. A factor score for a given observation takes into account the influence of all the variables for that observation. Absolute meanings of factor scores are difficult to interpret (Loder, 1971), but a clear interpretation of factor scores is possible when the scores are considered in relation to each other, i.e., a plot of factor scores gives an idea of the relative influence of different factors on the data.

RESULTS

General Observations

Complete data on primary productivity, chlorophyll a, and selected environmental variables are given in Table 1; their means, standard deviations, and coefficients of variation are shown in Table 2. The following features are immediately noticeable.

1. High primary productivity throughout the photic zone, down to the depth of 1% of the surface illumination, and relatively uniform concentration of chlorophyll a were observed at station P-1. At some stations a subsurface chlorophyll a maximum layer was observed, usually in the lower part of the photic zone. This layer was associated with high primary productivity, even at the 1% light level. At station P-6, samples from the 1% light level (ca. 37 m) could not be obtained because the depth at that station was only about 32 m. At stations P-1 and P-9, total primary productivity in the water column was very high, over 3 g C/m^2/half-day; at the remaining stations it ranged from 0.07 to 0.97 g C/m^2/half-day.

2. In general, surface layers were completely depleted of nitrate-N, whereas ammonium-N concentration was variable and sporadic. Only at stations P-1 and P-2 was nitrate-N concentration significant throughout the photic zone. Phosphate-P was present in substantial

Table 1. Data (n = 42) on primary productivity, chlorophyll a, and selected variables from the Chukchi Sea, July 1974; station number, station depth, and sampling depths for each station are also given. Variables include: primary productivity (PROD), chlorophyll a (CHL), percent of illumination level (% Light), total solar radiation (SOLRAD), Phosphate-P (PO_4-P), Silicate-SI (SIO_4-Si), Nitrate-N (NO_3-N), Nitrite-N (NO_2-N), Ammonium-N (NH_4-N), Temperature (TEMP), Salinity (SALI), and Sigma-T. An approximate average water temperature in the incubator during the primary productivity experiments is given in parentheses for each station.

Stn.	Depth	PROD	CHL	% Light	SOLRAD	PO4-P	SIO4-Si	NO3-N	NO2-N	NH4-N	TEMP	SALI	Sigma-T
P-1	0	530.64	17.35*	100.00	232.00	0.61	5.33	0.49	0.03	0.23	4.2	33.00	26.20
48 m	2	311.15	17.63	50.00	116.00	0.60	5.32	0.16	0.02	0.11	4.0	33.00	26.22
(4.0°C)	6	385.75	17.71	10.00	23.00	0.69	5.31	0.18	0.02	0.15	4.0	33.00	26.22
	11	54.21	18.66	1.00	2.00	0.66	5.42	0.16	0.02	0.18	2.8	33.20	26.49
	19	0.00	11.70	0.05	.10	1.67	25.46	11.68	0.12	1.05	0.2	33.10	26.59
P-2	0	12.27	1.53	100.00	118.00	0.58	2.82	0.24	0.02	0.28	6.8	32.60	25.58
54 m	4	15.04	0.90	50.00	59.00	0.59	2.81	0.20	0.02	0.17	6.8	32.60	25.58
(8.5°C)	12	5.98	1.06	10.00	12.00	0.61	2.86	0.19	0.03	0.17	6.7	32.60	25.59
	23	0.64	1.16	1.00	1.00	0.87	7.02	0.31	0.03	0.56	2.2	33.00	26.38
	38	1.10	1.23	0.05	0.05	1.00	4.01	1.27	0.04	1.61	1.7	32.80	26.26
P-3	0	3.80	0.30	100.00	97.00	0.63	10.71	0.00	0.03	0.17	0.9	27.60	22.14
54 m	4	3.56	0.51	50.00	48.00	0.64	11.15	0.00	0.03	0.11	0.0	27.80	22.30
(10.2°C)	14	2.27	0.25	10.00	10.00	0.66	12.32	0.00	0.02	0.06	-0.6	31.20	25.09
	27	43.67	13.97	1.00	1.00	1.72	25.47	7.74	0.13	2.86	-1.5	32.70	26.33
	45	0.01	1.00	0.05	0.05	1.97	44.29	10.35	0.16	2.86	-1.6	33.30	26.81

*Indicates that a portion of the water sample was spilled during filtration for chlorophyll a. These values were not included in statistical analysis.

Table 1, cont.

P-4 51 m (6.0°C)	0	6.69	0.30	100.00	103.00	0.59	10.53	0.02	0.02	0.08	2.4	28.00	22.38
	5	7.39	0.42	50.00	51.00	0.62	11.56	0.00	0.01	0.03	2.8	30.10	24.02
	17	9.07	0.45	10.00	10.00	0.61	13.76	0.00	0.02	0.04	-0.8	32.20	25.90
	33	95.61	40.17	1.00	1.00	2.20	26.92	8.26	0.16	1.42	-1.0	32.90	26.47
P-5 48 m (8.0°C)	0	3.13	0.55	100.00	154.00	0.76	6.98	0.00	0.05	0.06	4.7	31.40	24.77
	5	3.78	0.31	50.00	77.00	0.76	6.79	0.00	0.03	0.08	5.8	31.50	24.84
	17	2.84	0.47	10.00	15.00	0.85	21.32	0.00	0.01	0.05	-1.1	32.80	26.40
	33	21.00	8.65	1.00	1.50	1.93	42.60	13.13	0.21	2.24	-1.6	33.40	26.90
P-6 32 m (12.5°C)	0	5.34	0.28	100.00	175.00	0.42	2.16	0.10	0.00	0.06	4.1	28.60	22.72
	6	3.19	0.34	50.00	88.00	0.47	1.61	0.06	0.00	0.01	6.0	31.40	24.74
	18	5.01	0.49	10.00	18.00	0.79	7.75	0.19	0.03	0.03	2.0	32.80	26.23
P-7 43 m (6.8°C)	0	4.08	0.42	100.00	200.00	0.65	8.27	0.02	0.00	0.00	5.7	30.10	23.75
	5	6.74	0.32	50.00	100.00	0.65	8.32	0.00	0.00	0.00	5.7	30.20	23.83
	16	5.83	0.39	10.00	20.00	0.68	6.68	0.00	0.00	0.61	5.9	30.20	23.80
	31	1.85	1.09	1.00	2.00	0.88	12.06	0.39	0.03	0.61	1.0	30.30	23.30
P-8 48 m (4.5°C)	0	4.83	0.62	100.00	194.00	0.67	10.93	0.00	0.00	0.28	4.0	31.00	24.63
	5	6.32	0.61	50.00	97.00	0.67	10.92	0.00	0.00	0.23	4.0	31.00	24.63
	15	12.49	0.73	10.00	19.00	0.72	10.20	0.02	0.00	0.36	1.2	31.60	25.33
	30	4.82	1.52	1.00	2.00	0.78	11.14	0.29	0.01	0.28	0.5	32.00	25.69

Table 1, cont.

P-9 36 m (4.5°C)	0	38.92	0.78*	100.00	161.00	0.34	4.28	0.06	0.00	0.51	1.0	27.00	21.65
	5	5.83	0.44	50.00	80.00	0.56	3.76	0.00	0.00	0.144	0.4	28.20	22.64
	16	237.96	8.77	10.00	16.00	1.02	25.68	0.05	0.01	0.17	-1.4	33.20	26.73
	32	9.04	2.42	1.00	1.60	1.92	39.48	13.20	0.14	3.20	-1.6	33.60	27.06
P-10 44 m (4.2°C)	0	9.56	0.61	100.00	82.00	0.59	9.86	0.10	0.00	0.18	0.8	28.10	22.54
	6	8.72	0.66	50.00	41.00	0.60	9.91	0.06	0.00	0.18	1.2	29.40	23.57
	19	4.97	0.77	10.00	8.00	0.69	19.24	0.00	0.01	0.05	0.0	32.90	26.43
	37	10.644	7.56	1.00	0.80	1.91	40.36	13.12	0.02	2.11	0.0	33.00	26.52

Table 2. Means, standard deviations, and coefficients of variation of different variables (n = 42, except for chlorophyll *a* for which n = 40).

	Variable	Mean	St. Dev.	Coeff. Var.
1.	Primary Productivity, mg C/m^3/half-day	45.37	112.08	247.04
2.	Chlorophyll *a*, mg/m^3	4.17	4.98	190.17
3.	Percent Surface Illumination	38.31	39.62	103.42
4.	Solar Radiation, cal/cm^2/half-day	58.03	65.61	113.06
5.	Phosphate, mg-at PO_4-P/m^3	0.88	0.49	55.68
6.	Silicate, mg-at SIO_4-Si/m^3	13.18	11.47	87.03
7.	Nitrate, mg-at NO_3-N/m^3	1.95	4.23	216.92
8.	Nitrite, mg-at NO_2-N/m^3	0.04	0.05	125.00
9.	Ammonium, mg-at NH_4-N/m^3	0.56	0.86	153.57
10.	Temperature, °C	2.13	2.72	127.70
11.	Salinity, g/kg	31.39	1.92	6.12
12.	Sigma-T	25.05	1.56	6.23

amounts in the photic zone at all stations. An appreciable amount of Silicate-Si was present in all samples; only in the upper 6 m of station P-6 was its concentration low, about 2 mg-at/m^3. The amount of silicon in the photic zone varied considerably from station to station. The atomic ratio of nitrogen (nitrate-N, nitrite-N, and ammonium-N combined) to phosphorous was generally very low, less than one. At the bottom of the photic zone and below it, this ratio was higher; a maximum value of 8.61 was calculated for station P-9 at 32 m. The atomic ratio between silicon and phosphorous did not vary greatly within the photic zone; however, high values, from 20-28, were found in the lower part of the photic zone.

3. A strong gradient in the sigma-T in the upper layers, caused primarily by the melting of ice and the resulting low salinity of sea water, was noted for all stations near the ice edge. At stations occupied in open water, the water column in the upper 20-30 m was either nearly homogeneous (station P-1) or characterized by weak to moderate vertical stability and fairly uniform salinity (stations P-2, P-7, P-8).

4. The amount of chlorophyll was lower at stations occupied in open sea water (except station P-1). At stations near the ice edge, chlorophyll a concentration was higher: at stations P-3, P-4, P-5, P-9, and P-10, the amount of chlorophyll a in the

photic zone varied from ca. 80 mg/m^2 to ca. 332 mg/m^2. At the remaining stations (except station P-1), chlorophyll content in the photic zone was much lower, from 17-25 mg/m^2 (the value for station P-6 has been excluded because of the restricted sampling depths). At station P-1, the average concentration in the photic zone was high and resulted in a high extinction coefficient of light, and consequently this station had a shallow photic zone; on an area basis, chlorophyll a concentration in the photic zone was ca. 200 mg/m^2.

Photosynthesis-Light Relationships

The values of the parameters of Eqs. 1, 1a, and 2, and the asymptotic standard deviations of their estimates as calculated from nonlinear regression analysis are given in Table 3. It should be pointed out that observed incident solar radiation was used in these calculations; no corrections were made for the fraction, about 50% of the total solar radiation, utilized in photosynthesis (Westlake, 1965). Furthermore, losses attributable to the surface reflection of light and due to short-wave scattering and long-wave absorption of light energy in the upper few centimeters of seawater were not considered. These losses may result in an appreciable, but not large, reduction in the available light energy for photosynthesis.

Table 3. Estimated values and the asymptotic standard deviations of the parameters of equations describing the photosynthesis-light relationship (see text for details).

Steele (1962) -- Eq. 1 (two parameters)

$P_{max} = 18.49 \pm 1.53$

$I_{max} = 53.53 \pm 6.00$

Steele (1962) -- Eq. 1a (three parameters)

$P_{max} = 17.69 \pm 2.84$

$a = 0.0195 \pm 0.0000$

$a' = 0.0187 \pm 0.0021$

Vollenweider (1965) -- Eq. 2 (three parameters, assuming n = 1)

$P_{max} = 54.45 \pm 13.44$

$a = 0.023 \pm 0.0000$

$\alpha = 0.053 \pm 0.021$

It should be noted from Table 3 that two parameters of Eq. 1a, $\underset{\sim}{a}$ and $\underset{\sim}{a}'$, have similar estimated values. The reciprocals of the estimates of these parameters are 51 and 53, respectively--values that are very close to the estimated value of I_{max} of Eq. 1.

Figure 2 shows the specific photosynthetic rate versus light intensity curves for Eqs. 1 and 2, based on estimates of their parameters (Table 3). The optimal photosynthetic rate, as seen from the curve for Eq. 2, is about 31% of the estimated P_{max} value; its numerical value, ca. 17 mg C/mg Chl a/ half-day, is comparable to the P_{max} value of Eqs. 1 and 1a (Table 3).

Visual inspection of the difference between the observed and computed values of photosynthetic rates (Fig. 2) indicated that curve II (for Eq. 2) consistently underestimated the observed values; i.e., (Y-f) was large. The statistical significance of their difference was noted by testing the null hypothesis that the difference (Y-f) was equal to zero by a t-test. It was found that the average difference between the observed and computed values, 1.83, was significant at the 5% level (t = 2.23*). For Eq. 1 (curve I) the average difference, 0.93, was not statistically significant (t = 1.09 N.S.); i.e., it was not significantly different from zero.

Factor Analysis

A set of 40 observations on 10 variables from 10 stations was analyzed by factor analysis. Two of the variables listed in Table 1, percentage of

light intensity and value of sigma-T, were excluded from factor analysis because they did not represent independently measured quantities.

A notable feature of the correlation matrix (Table 4) is the highly significant correlation among the micronutrients studied; for example, PO_4-P has strong correlation with SiO_4-Si, NO_3-N, NO_2-N, and NH_4-N. Primary productivity was significantly correlated with chlorophyll a concentration alone; most noticeably it was uncorrelated with both solar radiation and micronutrients. The significant negative correlation between solar radiation and micronutrients reflected the high concentration of micronutrients in deeper layers. The significant negative correlation of solar radiation with salinity showed the effect of ice melting in the surface layer; its positive correlation with temperature indicated the effect of isolation.

Two eigenvalues in the correlation matrix were larger than 1.0 (Table 4); therefore, two factors were selected (see Loder, 1971; Harmon, 1967). Variable loading coefficients of the factors, after the varimax rotation, are presented in Table 5. Since a suitable test for the significance of the loading coefficients is lacking, a value of 0.80 was selected arbitrarily to indicate the dominant variables in each factor. This value provided a convenient, though highly subjective, criterion for selecting the significant variables, but was appropriate in view of the calculated loading coefficients (Table 5). Based on this criterion, the composition of the two factors in terms of the observed variables is given in Table 6.

Table 4. Correlation matrix of 10 variables studied for factor analysis. Critical value of the significance of the correlation between any two variables in this matrix, with n-k-l = 27 degrees of freedom, is 0.37 at the 5% and 0.47 at the 1% significance level. Eigenvalues of the correlation matrix are also given.

	PROD	CHL	SOLRAD	PO_4-P	SiO_4-Si	NO_3-N	NO_2-N	NH_4-N	TEMP	SALI
PROD	1.00									
CHL	0.57	1.00								
SOLRAD	-0.04	-0.27	1.00							
PO_4-P	0.002	0.51	-0.49	1.00						
SiO_4-Si	-0.03	0.26	-0.46	0.88	1.00					
NO_3-N	-0.06	0.38	-0.40	0.94	0.87	1.00				
NO_2-N	-0.01	0.46	-0.40	0.88	0.74	0.84	1.00			
NH_4-N	-0.08	0.27	-0.44	0.89	0.79	0.88	0.80	1.00		
TEMP	0.01	-0.23	0.59	-0.59	-0.72	-0.51	-0.49	-0.51	1.00	
SALI	0.29	0.41	-0.51	0.52	0.41	0.45	0.45	0.44	-0.15	1.00
<u>Eigenvalues</u>										
	5.62	1.64	0.94	0.76	0.42	0.24	0.18	0.13	0.05	0.02

Table 5. Variable loading coefficients and their sums of squares for two-factor matrix after the varimax rotation.

Variable	Factor I	Factor II
Primary Productivity	-0.192	0.874
Chlorophyll *a*	0.282	0.821
Solar Radiation	-0.568	-0.253
Phosphate	0.944	0.234
Silicate	0.922	0.062
Nitrate	0.928	0.116
Nitrite	0.859	0.205
Ammonium	0.909	0.064
Temperature	-0.703	-0.016
Salinity	0.437	0.585
Sum of squares	5.292	1.962

Table 6. The composition and loading coefficients of the dominant variables in two factors. The percent of total variation explained by each factor, and the percent contribution of the dominant variables to the make-up of each factor are also given.

	Factor I		Factor II	
PO_4-P	0.944	PROD	0.874	
NO_3-N	0.928	CHL	0.821	
SiO_4-Si	0.922			
NH_4-N	0.909			
NO_2-N	0.859			
Percent of total variation explained	57.45		19.82	
Percent contribution to each factor	78.75		73.29	

The first factor consisted of the micronutrients and the other represented phytoplankton productivity. These two factors, which included seven variables, accounted for 77% of the total variability in the data. The dominant variables of each factor represented between 73 and 79% of the sum of squares of all variables in that factor. For example, in factor II the sum of squares of the coefficients of the dominant variables, primary productivity and chlorophyll a, is 1.438, which is 73% of the total sum of squares, 1.962 (Table 5).

Including the two formerly deleted "variables" in factor analysis resulted in the formulation of three factors. The dominant variables of the third factor were solar radiation and percentages of light intensity at sampling depths. This was expected because the amount of solar radiation and the percentage of illumination level at sampling depths were highly correlated, r = 0.92 (M.J. Hameedi, unpublished data). Nevertheless, the three factors representing nine variables accounted for about 75% of the total variability in the data, and the two dominant variables of the third factor contributed only 52% of the sum of squares of the loading coefficients for that factor, a percentage much lower than those calculated from the previous analysis, 73-79%.

The plot of factor scores for 40 observations in terms of factors I (nutrient factor) and II (phytoplankton factor) are shown in Fig. 3. A notable feature of this plot is the clustering of 29 of the 40 observations. This cluster represents the prevalence of nutrient and phytoplankton

regimes in the Chukchi Sea at the time of our observations; i.e., a majority of observations were characterized by low nutrient concentrations and low chlorophyll a and primary productivity levels. Six observations with high scores, larger than 1.0, for factor I but low scores for factor II represent observations at the 1% and 0.05% illumination levels--a notable exception being station P-2, where generally low nutrient concentrations were observed at the 0.05% illumination level (38 m). There were four observations which had high scores for factor II but low scores for factor I. Three out of these four observations were from a single station, P-1 at 0, 2, and 6 m; the fourth was from station P-9 at 16 m. Only a single observation, station P-4 at 33 m, was characterized by high scores for both factors.

DISCUSSION

Primary Production

Dunbar (1968, Ch. 4), in a comparison of organic productivity in the polar regions, stated that marine primary production in the Arctic Ocean was much lower than in the Antarctic. The limited number of observations on the rate of primary productivity in the arctic waters, especially those made from the ice island T-3, seem to support this view (Pautzke, 1974; English, 1961). Published research work on this subject for the Chukchi Sea is even more scant. Dawson (1965) provided data on chlorophyll and

primary productivity from this area. Because Dawson's data are only presented in a technical report, reference to his work will be given in detail. His samples for primary productivity measurements were incubated at various times of the day and the incubation period varied from 2-10 hours. He combined the data from the in situ and simulated in situ experiments to signify natural-light incubations. Chlorophyll concentration was determined by the method of Creitz and Richards (1955), and the rate of carbon fixation by the procedure outlined by Steemann Neilsen (1952). Both of these methods are now generally believed to provide erroneous results: the method of Creitz and Richards (1955) gave higher estimates of chlorophyll a than the method recommended by SCOR-UNESCO (Banse and Anderson, 1967), and the primary productivity values, based on ampoule standardization utilizing the barium carbonate technique, are underestimated (Steemann Neilsen, 1965). The differences in the analytical procedures and incubation techniques notwithstanding, data presented here and those by Dawson (1965) both point toward the generally low phytoplankton productivity and biomass in the Chukchi Sea in summer: for example, during July-August 1960, average primary productivity and chlorophyll a concentration in the water column were 1.5 mg $C/m^3/h$ and 2.1 mg/m^3, respectively.

The influence of temperature on primary productivity is generally considered to be very small (Dunbar, 1968), although it may set the upper limit on phytoplankton growth rate (Eppley, 1972). The effect of temperature is not apparent in the present data (Table 1): high values of primary

productivity were observed at both very low, for example -1.4°C (P-9, 16 m), and moderate, for example 4.2°C (P-1, 0 m), temperatures. Conversely, low productivity was observed at similar temperatures at other stations: for example, 3 mg C/m^3/half-day at 5.7°C (P-5, 0 m), and 5 mg C/m^3/half-day at 0°C (P-10, 19 m). In the Weddell Sea (Antarctica), rich phytoplankton growth has been observed at a seawater temperature of -1.7°C (El-Sayed, 1971).

Light also does not seem to be a limiting factor in this area during summer. The mean value of surface solar radiation during our observations was ca. 480 ly/day (n=12), with a range from 152 to 716 ly/day. Similar values were obtained by Dawson (1965) during August 1960 and July 1961. These values are comparable to the maximum average radiation value, 0.36 ly/min, for temperate regions (Sverdrup et al., 1942, Table 25).

The nutrient supply into the photic zone can be regarded as the dominant factor that determines the level of primary productivity in the Chukchi Sea. From Table 1, it can be calculated that the atomic ratio of inorganic nitrogen to phosphorus in the deeper layers was about 8. In water samples obtained from near the bottom of the Chukchi Sea, the ratio is about 10 (Kinney et al., 1970). No information is available regarding the nutrient or elemental pools of the dissolved and particulate matter in the Chukchi Sea. The nitrogen-to-phosphorus ratios are slightly smaller but comparable to the ratios found below the photic zone off Washington and

Oregon coasts in summer (Conomos et al., 1972). The influx of micronutrients into the surface layers is retarded, since the Arctic Ocean, in general, is vertically stable at all times of the year (Kusunoki, 1962), and the Chukchi Sea, in particular, becomes vertically highly stratified in summer due to the melting of ice (Fleming and Heggarty, 1966). The replenishment of nutrients by vertical eddy diffusion is therefore likely to be slow, especially if the eddy transfer coefficient is of the order of 1 cm^2/sec (Solomon and Garrison, in press). The slow turnover of deeper water is also reflected in the long residence time and low dissolved oxygen content of the Chukchi Sea's deeper waters (Aagaard, 1964). It is possible, however, that a large localized source of nutrients could move into the surface layers by vertical advection. According to Fleming and Heggarty (1966), a large-scale divergence of surface water in the southwestern Chukchi Sea, corresponding to the convergence of warm, less saline water on the Alaskan coast, results in the upwelling of surface waters along the Siberian coast. This phenomenon has not been verified by actual measurements, but such a situation seems to exist at station P-1 where the relatively homogeneous waters are associated with appreciable nitrate-N concentrations in the photic zone. Similar high nitrate content in the upper layers and a uniform vertical density profile in the upper 40 m were also observed off the Siberian coast in summer 1968 (see data for station 8 in Burrell et al. (1972)).

In a few cases, concentration of silicon in the photic zone was also very low (see Table 1), indicating the possibility of double (or multiple)

nutrient limitation of algal growth. Davis (1974) has suggested the threshold concentration for silicate limitation in marine diatoms to be about 3 mg-at Si/m^3. Multiple nutrient limitation, which has been recognized in lakes (Fuhs _et al._, 1972) and in culture experiments (Droop, 1973) would cause formidable problems in predicting algal growth and trophic dynamics for the Chukchi Sea with the present concepts of modeling.

A comparison of chlorophyll content in the photic zone at various stations indicated higher amounts and a significant subsurface accumulation at stations occupied near the ice edge than those in open water. Assuming a significant removal of phytoplankton by zooplankton grazing and noting the observed moderate rates of primary productivity, the observed chlorophyll distribution near the ice edge appeared to be exceptionally high. Preliminary examination and analysis of zooplankton samples obtained from stations near the ice edge have indicated a variable abundance of zooplankton population: an average of 695 to 3176 individuals/m^3 and an average mass of 5 to 35 mg/m^3 in the upper 40 m (M. J. Hameedi, unpublished data). These values cover the range found at other stations, and are comparable to values found in oceanic waters of the northeast Pacific Ocean where the effect of zooplankton grazing on phytoplankton is well marked (Hameedi, 1974). Thus it does not seem probable that the sinking of algae in the water column, due to reduced grazing pressure, would be the major cause of the subsurface accumulation and the high content of chlorophyll _a_ near the ice edge. Rather, one should also consider the possible contribution of the extensive flora

that grows near the bottom of solid, unbroken ice. Such flora was frequently observed during our cruise (but was not sampled) as a brown layer on overturned masses of sea ice. The microalgae growing at the bottom of sea ice have been recognized as the commonly occurring species of diatoms, both in the arctic and the antarctic oceans (Horner and Alexander, 1972; Meguro et al., 1967; Bunt and Wood, 1963). The chlorophyll a content of this layer is usually greater than 100 μg/ℓ; values as high as 1460 μg/ℓ have been reported (Meguro et al., 1967; Apollonio, 1965). Based on a few observations, Clasby et al. (1975) have reported primary productivity values between 0.3 and 14.9 mg $C/m^2/h$ for the algal community that lives on the underside of sea ice near Pt. Barrow, Alaska. Growth of these algae is not considered to be nutrient limited (Horner, 1973). According to Meguro et al. (1967), diatoms growing in sea ice are free from grazing pressure and represent net primary production for spring and early summer. During the ice melt, the accumulated phytoplankton is liberated into the sea and may appear as an algal bloom.

In view of the data presented in Table 1, the contribution of sea ice algae to the total chlorophyll a content in the Chukchi Sea can be considered substantial and highly significant. The stay of these cells in the water column may not be very long. In a later cruise (18-20 Sept. 1974) during the ice-free period in the Chukchi Sea, the subsurface chlorophyll maximum had completely disappeared. In the upper 40-45 m, the chlorophyll concentration was uniformly low: it varied between 0.43 and 2.15 mg/m^3. Nitrate-N concentration in the photic zone was lower

than that observed in July. These results are based on data (n=44) from nine stations: six stations along a line northwest of Wainwright, Alaska, and three along a line approximately normal to Pt. Barrow, Alaska. No primary productivity experiments were conducted on this cruise. The sinking of the liberated cells from sea ice in large quantities may become a significant source of benthic algal biomass and primary productivity. Matheke (1973, in Horner 1973) has found that, off Pt. Barrow, benthic primary productivity was at least twice as high as that of the phytoplankton; chlorophyll a was about 30 mg/m^3 in the benthic zone, and 0.1 to 5.2 mg/m^3 in sea water.

PHOTOSYNTHESIS-LIGHT RELATIONSHIPS

A notable feature of the photosynthesis-light curves (Fig. 2) for the Chukchi Sea phytoplankton is the low maximum specific primary productivity. My calculations of Dawson's (1965) data on the *in situ* and simulated *in situ* primary productivity measurements from July-August 1960 (n=31), using the nonlinear regression method outlined earlier, gave a P_{max} value of 1.32 mg C/mg Chl a/h and an I_{max} of 24.32 ly/h (Fig. 4). Since these data did not show marked photoinhibition, I also applied the Michaelis-Menten equation for enzyme kinetics,

$$P = P_{max} \frac{I}{(I + K)} ,$$

to these data. Using the nonlinear regression, I obtained a value of 1.36 mg C/mg Chl a/h for P_{max}, the maximum photosynthetic rate, and 4.45 ly/h for K, a constant that represents the light intensity at which P equals 1/2 P_{max}. The resulting curve is shown in Fig. 4.

Assuming an incubation period of 12 h and a P_{max} of 18 mg C/mg Chl *a*/half-day, an hourly value of 1.5 mg C/mg Chl *a*/h can be approximated for the data presented in this paper. This value is about 40% of the average value of 3.7 mg C/mg Chl *a*/h reported by Ryther and Yentsch (1957) for freshwater and marine phytoplankton. However, the P_{max} values calculated herein are in fair agreement with the range of values (1.0-1.5 mg C/mg Chl *a*/h) given by Steemann Nielsen and Hansen (1959) for arctic phytoplankton. Compared to values obtained in the high Arctic, the Chukchi Sea values are low: T. Smith and T. S. English (unpublished manuscript) reported values from 3.6 to 7.2 mg C/mg Chl *a*/h for data obtained in summer 1971, and Pautzke (1974) reported a value of 3.8 mg C/mg Chl *a*/h for data obtained in summer 1973 from the ice island T-3. In both of these studies, Steele's (1962) equation was used to describe the data which were obtained from artificial (cool-white fluorescent) light incubations. Apart from the possible differences in the composition of phytoplankton populations in the Chukchi Sea and the higher Arctic (no detailed information is presently available on the subject), the large difference between P_{max} values of the two regions may be due to the differences in the incubation techniques employed. P_{max} values obtained from simulated *in situ* experiments are generally lower than those from laboratory incubation. Hameedi (1974) found that estimates of P_{max} of oceanic phytoplankton from simulated *in situ* experiments (half-day incubation) were 30-50% lower than those estimated from laboratory incubation of 2-3 hours under artificial light. The possible effects of the quality of light, duration of experiments, and incubations at different times of day are discussed by Hameedi (1974).

As only about 50% of the total solar radiation is photosynthetically active, the revised values of I_{max} for the Chukchi Sea phytoplankton can be calculated as 27 ly/half-day or 2.25 ly/h (see Table 3). This value is quite a bit lower than the often-quoted average for marine phytoplankton--2000 ft candles or ca. 7.7 ly/h, using the conversion factor of 1 ft candle= 6.45×10^{-5} ly/min (Strickland, 1960). For higher arctic phytoplankton, I_{max} values have been found to be 2.30-2.55 ly/h (T. Smith and T. S. English, unpublished manuscript; Pautzke, 1974). But the value of I_{max} calculated from Dawson's (1965) data for the Chukchi Sea is much larger--12 ly/h. A possible explanation for this difference is the large range of surface solar radiation values, 6-29 ly/h (photosynthetically active), to which primary productivity samples were exposed. The photosynthetically active surface solar radiation in the present data (Table 1) ranged from 41 to 116 ly/half-day, i.e., illumination varied by a factor of 2.8. In Dawson's data, it varied by a factor of 4.8. Furthermore, photoinhibition of photosynthesis was not well marked in Dawson's data; therefore I_{max}, as defined by Eq. 1, was not clearly established. The maximum light intensity used by Pautzke (1974), 1143 ft candles (4.42 ly/h), is fairly representative of the range of solar radiation values obtained in the present study. It should be pointed out that the spectral range of cool-white fluorescent light is from 350-750 mμ, and is comparable to the range of the photosynthetically active part of solar radiation, 380-720 mμ (Strickland, 1960). Pautzke's illumination values should therefore be compared with one-half the solar radiation values in Table 1.

In view of the low I_{max} values and marked photoinhibition at moderate light intensities, it can be surmised that the Chukchi Sea phytoplankton is "shade-adapted." Such cells can efficiently utilize solar radiation at very low light intensities. This adaptation is especially significant when we consider the high light extinction coefficients of snow and ice, 0.29 and 0.012 cm^{-1}, respectively (Weller and Parker, 1972), which may permit less than 1% of the surface solar radiation to reach the subjacent sea water during spring and early summer. It has also been shown that algae in low-temperature environments grow at much lower light intensities (Pechlaner, 1971). The very low compensation light intensities of such algae, 0.013 to 0.026 ly/h, can only be explained by extremely low respiratory rates (Steemann Nielsen, 1974). For the Chukchi Sea phytoplankton, these two features provide useful adaptations for existence in cold and dimly-lit sea water. An important aspect not covered in studies of the photosynthesis-light relationship in the Chukchi Sea, and the arctic area in general, is the possible effect of nutrient limitation on I_{max}. Steemann Nielsen (1974) has pointed out that nutrient-limited algae show a more pronounced light inhibition. Such effects can not be evaluated for the Chukchi Sea phytoplankton until data on nutrient limitation on algal growth and flux and release of the limiting element are obtained.

Comparison of Equations 1 and 2

The two equations used to describe the photosynthesis-light relationship described the data well, although Eq. 2 underestimated the observed

specific photosynthesis rate by a small, but significant, amount. Equation 1 has generally been considered to provide an accurate fit for data up to light saturation, but it has been pointed out that it overemphasizes light-inhibition. Its modification, as proposed by Vollenweider (1965), was aimed at providing a better fit to experimental data. However, it will be noted that the two new parameters of the modified Steele equation have very similar values: 0.0195 and 0.0187 for $\underset{\sim}{a}$ and $\underset{\sim}{a}'$, respectively. It is not possible to determine the statistical significance of the difference, since the usual tests to obtain conclusions on stated level of significance are generally not applicable to the nonlinear estimates (Draper and Smith, 1966). As pointed out earlier, however, the reciprocals of these estimates are close to the I_{max} value estimated for Eq. 1. It therefore does not seem advisable to use a more complex function to describe the photosynthesis-light relationship when its simpler and widely used form provides similar results. This is especially relevant in view of the general criticism, based primarily on the variability in the P_{max} of both equations (Bannister, 1972).

The problem with Vollenweider's equation, Eq. 2, was the difficulty in estimating all the parameters. This can be overcome by writing a separate computer program to estimate the parameters, similar to the one suggested by Fee (1973). More important, however, the physiological significance of all the parameters is not well defined. For example, both $\underset{\sim}{n}$ and α in Eq. 2 are related to photoinhibition of photosynthesis, but neither is an experimentally verified physiological factor. It is possible that $\underset{\sim}{a}$ in Eq. 2 represents $1/I_{max}$ or I_k' (following Vollenweider's (1965) terminology, p. 437), in which case it is a parameter similar to

that of Eq. 1. However, this would occur only when $\underset{\sim}{a} = \alpha$, and, as seen in Table 3, estimated values of these parameters are quite different. In fact, according to Eq. 2, the optimal photosynthesis rate occurs at ca. 30 ly/half-day (Fig. 2), a value very close to the average of the reciprocals of $\underset{\sim}{a}$ and α, 43 and 19, respectively. Equation 2, as applied to the present data, is essentially empirical and does not elaborate on the physiological features of the growth of phytoplankton as related to incident radiation. Some recent transformations of photosynthesis-light equations (Bannister, 1972) can not be easily applied to most field data, and retain the weaknesses of the original equation.

Factor Analysis

As stated earlier, the primary aim of factor analysis of the data presented here was to provide a simple and effective rationale for groupings and trends among the bioenvironmental variables studied in the Chukchi Sea. Such an analysis was especially useful for the present data because the fundamental relationships between variables, such as nutrient limitation of primary productivity, could not be analytically studied. It should be pointed out that the number of variables studied herein is small compared to other recent studies involving factor analysis; for example, 66 variables by Stevenson *et al*. (1974) and 130 by Smith and Fisher (1970).

The entire variable set was defined by nutrient and phytoplankton factors alone (Table 6). The variable composition of the second factor can be altered if one considers a loading coefficient of 0.4 to be critical

(Fisher, 1973; Sokal et al., 1961). Under this assumption, the first factor would have a high correlation with all physical and chemical variables (Table 5). Such a grouping of all the environmental variables (28) into one factor was noted by Smith and Fisher (1970). The loading coefficient of salinity is such that it is correlated with neither factor if one considers the critical value to be 0.8, but it is correlated with both if 0.4 is considered the critical value. This could be due to its only marginally significant correlation with other variables (Table 4).

The effect of the varimax rotation on the accentuation of modality in loading coefficients was not very large. For example, in the case of factor II, loading coefficients of primary productivity and chlorophyll a in the unrotated form were 0.89 and 0.71, respectively; the remaining variables had values between 0.05 and 0.20, except salinity which had a value of 0.43 (M. J. Hameedi, unpublished data). After varimax rotation, the loading coefficients of primary productivity and chlorophyll a were 0.87 and 0.82, respectively; the other variables, except salinity, varied between 0.02 and 0.25 (Table 5).

The plot of factor scores for the two factors (Fig. 3) showed a separation of observation: data from low illumination levels at most stations and especially those for station P-1 were easily distinguished from the prevalent conditions of low primary productivity and low nutrient levels. No further analysis of factor scores was carried out, since they are only estimated values and therefore cannot be used for further statistical tests to determine the trends in their distribution (Van Andel and Nelissen, 1973). Loder (1971) classified his observations in the

Chuckchi Sea into different categories of regions (southern and northern) and depths (shallow and deep) on the assumption that the physical and chemical characteristics of water masses within these categories were similar. This was done to provide a clearer interpretation of factor score plots. Such a grouping seems arbitrary, especially for the Chukchi Sea where the physical structure of the water masses and the mode of their formation are not yet well known, and was not attempted for the present set of data.

From the results obtained in this study, the usefulness of factor analysis in ecological research appears to be limited. Only when almost nothing is known about the data, does it provide a rational, objective, and parsimonious interpretation. Even so, the factors extracted from the data may simply be hypothetical constructs that summarize the information in the correlation matrix, and may not represent the salient feature of an ecosystem based on cause-effect relationships (Sokal et al., 1961). The two factors extracted from the present data were intuitively apparent, so the factor analysis can be regarded as an exercise to provide a mathematical rationalization. The advantages of factor analysis become immediately obvious when the number of variables in a study is large, say 25 or more, in which case the intuitive grouping of the variables becomes difficult and highly subjective.

SUMMARY

1. Data on phytoplankton primary productivity, chlorophyll a, solar radiation, inorganic micronutrients, temperature, salinity, and density were obtained from 10 stations (n = 42) in the Chukchi Sea during July 1974.

2. In general, primary productivity was very low: between 0.07 and 0.97 g C/m^2/half-day. Only at two stations, one off the Siberian coast and the other with an extensive ice cover, was primary productivity very high, over 3 g C/m^2/half-day. Nitrogen limitation on algal growth was indicated.

3. Chlorophyll a concentration in the photic zone varied widely. At stations near the ice edge, high concentrations (80-332 mg/m^2) and a subsurface maxima (8-40 mg/m^2 of chlorophyll a were observed. In open water, chlorophyll a varied between 17 and 25 mg/m^2. The possible contribution of the sea-ice flora to the algal biomass in the water column is discussed.

4. The relationship between the specific photosynthetic rate of phytoplankton and the incident solar radiation was studied in relation to the equations proposed by Steele (1962) and Vollenweider (1965). The parameters of these equations were calculated by a nonlinear regression technique. The maximal photosynthetic rate (17-18 mg C/mg Chl a/half-day) and the optimal light intensity (ca. 50 langleys/half-day) indicated that phytoplankton was adapted to low light intensities. Steele's (1962) equation provided a better fit to the observed data.

5. Factor analysis of a set of 40 observations on 10 variables resulted in the formation of two factors. The first factor included phosphate, nitrate, silicate, ammonium, and nitrite; the second factor included primary productivity and chlorophyll a. These two factors accounted for 77% of the total variability in the data. The applicability and usefulness of factor analysis to ecological data are discussed.

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Acknowledgments

The research reported in this paper was supported by the Office of Naval Research (Code 461), U.S. Navy, Contract No. N00014-75-C-0187, Project NR 307 357 (S.R. Shah, Principal Investigator). I wish to thank Prof. George C. Anderson of the Department of Oceanography, University of Washington, for the use of the facilities and equipment in his laboratory.

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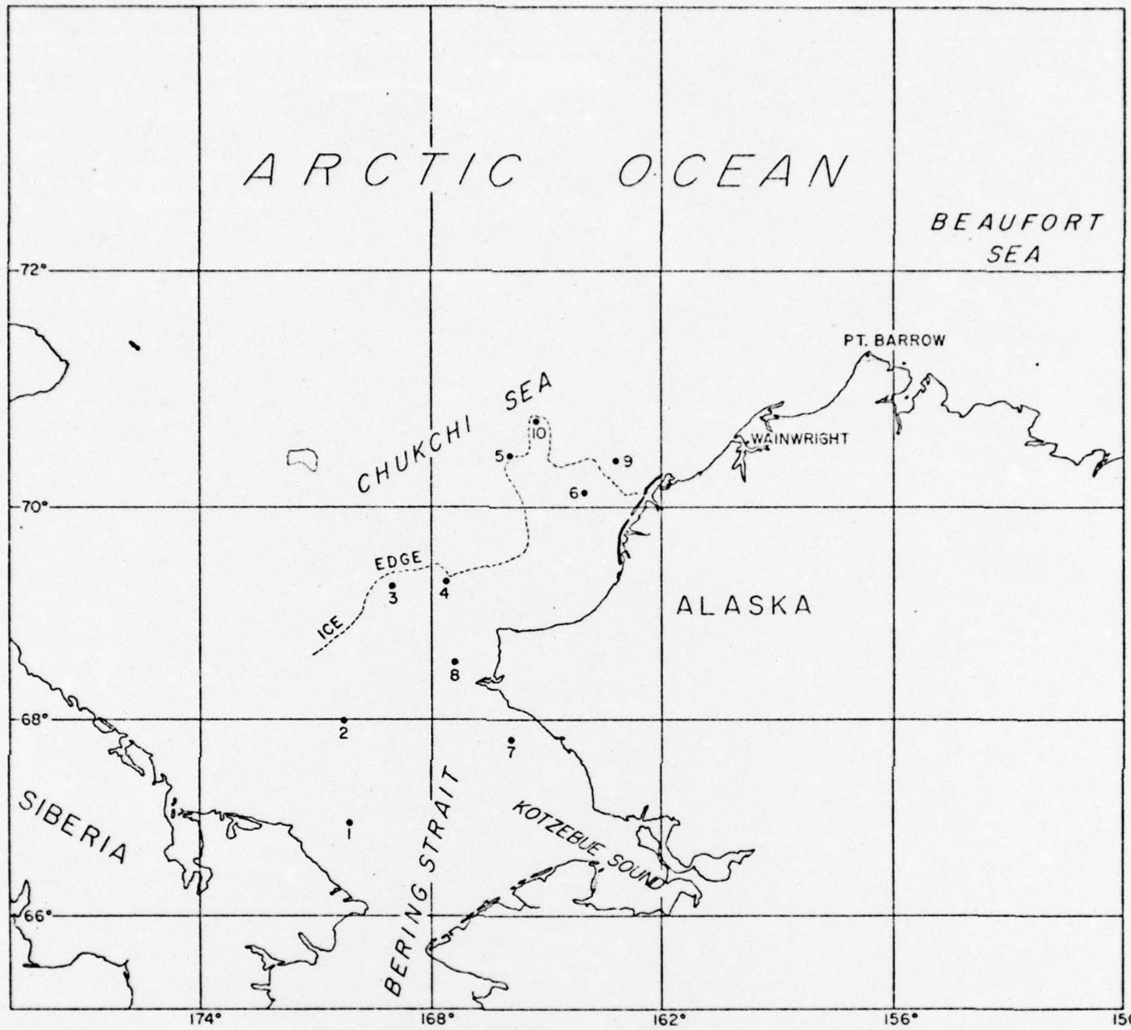
Figure Legends:

Figure 1. Location of primary productivity stations in the Chukchi Sea, July 1974.

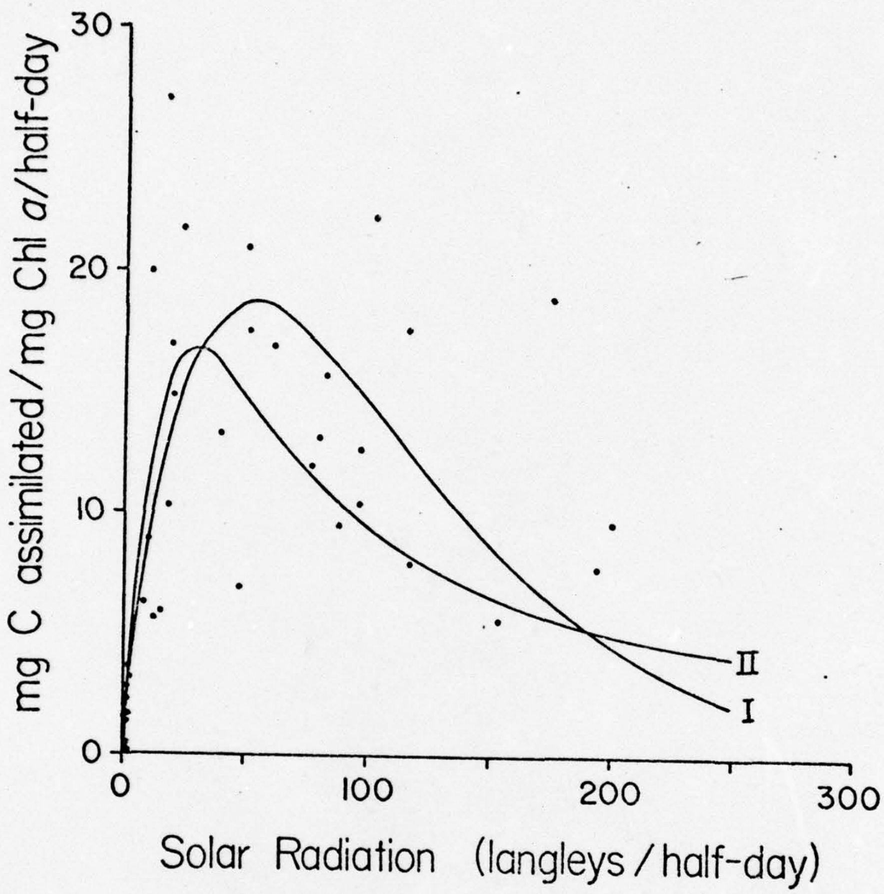
Figure 2. Specific photosynthetic rate as a function of solar radiation, July 1974. Curve I: Steele's equation. Curve II: Vollenweider's equation with three parameters, assuming $n = 1$. See Table 3 for parameter values and text for details.

Figure 3. Factor scores plot for Factor I (nutrients) and Factor II (phytoplankton) for the Chukchi Sea, July 1974.

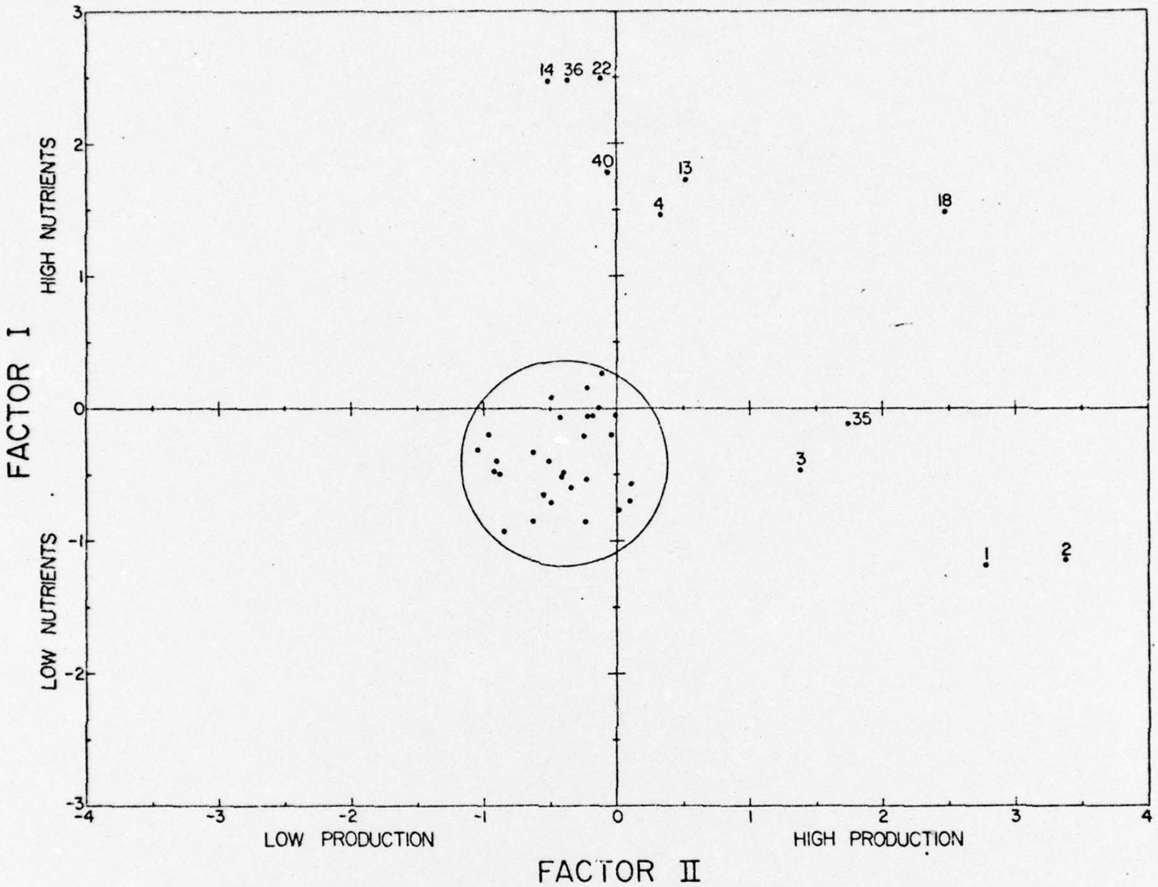
Figure 4. Specific photosynthetic rate as a function of solar radiation based on data for July-August 1960 from Dawson (1965). Curve I: Steele's equation. Curve II: Michaelis-Menten equation.



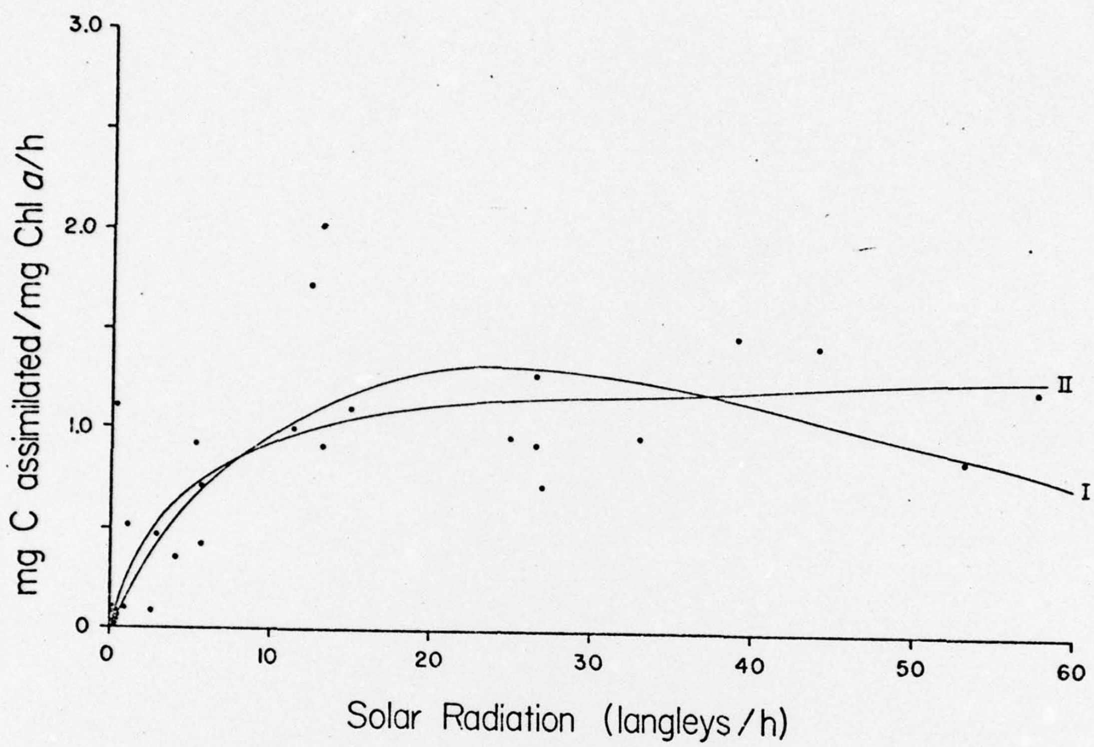
Hameedi, Fig. 1



Hameedi, Fig. 2



Hameedi, Fig. 3



Hameedi, Fig. 4

BIOACOUSTIC STUDIES IN THE CHUKCHI SEA

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Published in Arctic Bulletin, Vol. 2, No. 7, 1975, p. 8-10

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The Applied Physics Laboratory at the University of Washington has actively participated in the Marginal Ice Zone Pacific Project since 1971. This project is a comprehensive study of the physical oceanography and acoustic properties of the Chukchi and the adjacent southwestern Beaufort Seas. Initial acoustic data taken in summers 1971 and 1972 were used in assessing the volume scattering strength (VSS) in the water column at different sound frequencies.* Analysis indicated high scattering strengths, up to -42 dB (re m^{-1}), and probably a high density of biological scatterers.

One of the present research projects** is quantitatively evaluating biological and acoustic data from the Chukchi Sea. Special emphasis is also placed on the gross trophic structure of the plankton ecosystem and evaluating the effect of significant environmental variables on the biological population. With theoretical calculations of sound scattering and data from simultaneous observations of the physical and biological parameters, a preliminary forecasting model of volume scattering strength in the water column will be formulated.

The Chukchi Sea was chosen for these observations because:

- Previous measurements indicated high acoustic coefficients, at least during summer.
- The general physical properties of the seawater and the northward flow from the Bering Sea to the Arctic Basin are well known. For example, it is generally agreed that the northward water transport is on the order of 1 million cubic meters/second, primarily because of the barotropic mode. In general, there is a convergence of warmer and less saline water on the Alaskan coast and an apparent divergence along the northeast Siberian coast. Data on the thermal microstructure of the water masses and the general mixing processes in the marginal ice zone of the Chukchi Sea are being studied at the Laboratory.
- There is a well-defined cycle of seasonal variation in the solar radiation.
- The area is usually ice-covered for 7 to 8 months of the year. A significant amount of plankton primary productivity is initiated when ice starts to break-up, and sufficient light penetrates the surface waters. The period of primary productivity is short and is characterized by rapid growth and decline in the plankton populations.
- The Chukchi Sea is a shallow basin oriented northwest to southeast, with an average depth of about 50 meters. Because of this restricted environment, the extent of vertical migration by zooplankton is limited, and collection of specimens from a given layer of high acoustic scattering does not require complex gear or time-consuming operations. A simple collecting device, such as a single-stage closing net, can easily be regulated for sampling from a desired layer.

Field Trip and Measurements

Field observations were made during July 1974 aboard the USCGC *Burton Island*. The 18-day cruise began on July 12 at Nome, Alaska, and ended at Barrow, Alaska. The location of the stations is shown in Figure 1. The primary objective was to obtain descriptive information on biological communities and processes in the Chukchi Sea during summer. Comprehensive data were collected on the incoming solar radiation, in-

* The volume scattering strength of a cubic meter of water is 10 log A, where A is the differential cross section for backscattering per cubic meter. Its units are decibels (dB) re m^{-1}.

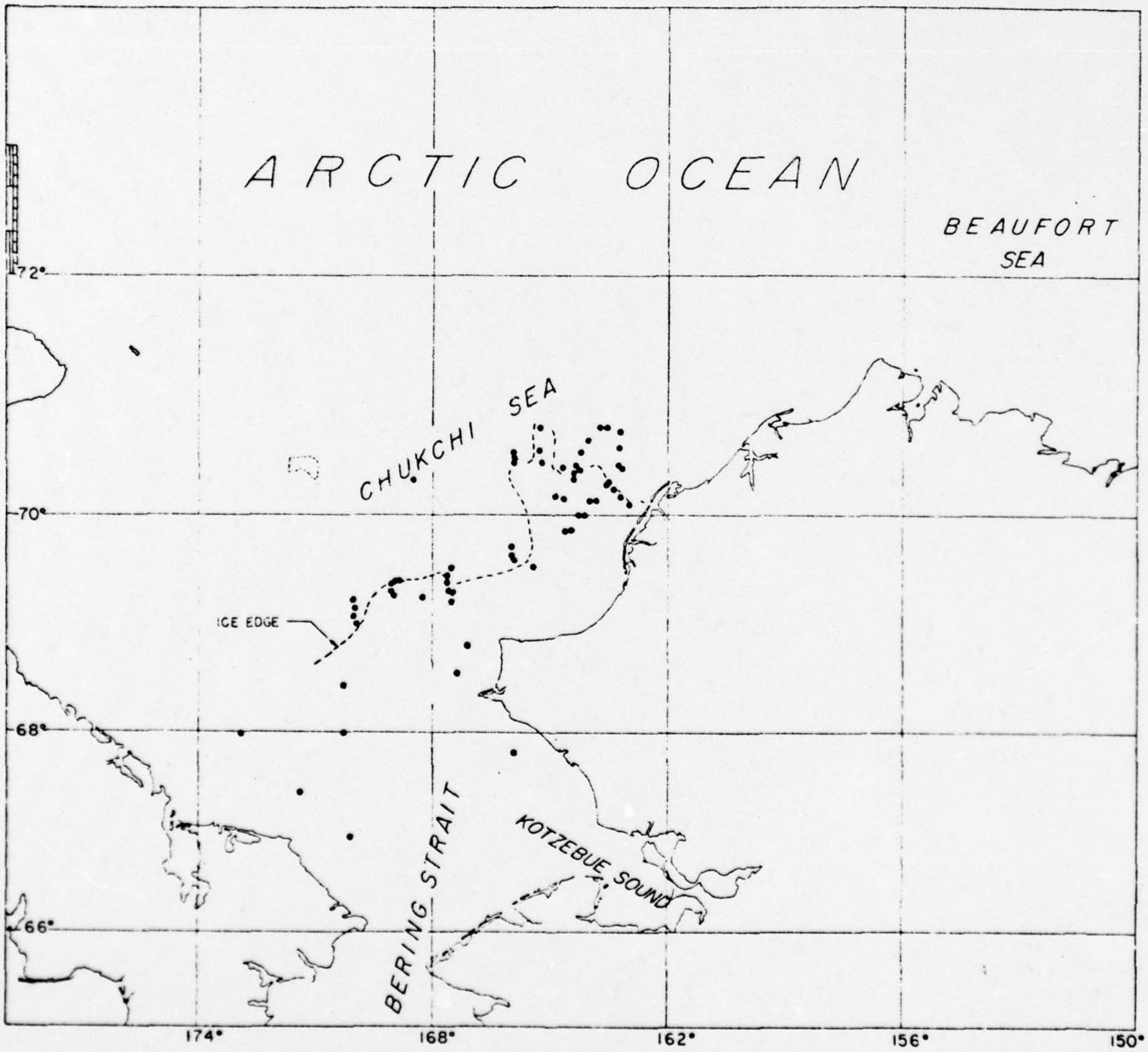
** The research described is supported by a contract from the Arctic Research Program (code 461), Office of Naval Research, U.S. Navy, Arlington, Va.

organic micronutrients, and the density of plankton populations. The data were used in assessing the rate of primary productivity as related to the environmental variables and in estimating the fraction of phytoplankton consumed by herbivores in the pelagic region. Acoustic scattering measurements were made to deduce generalities about the spatial variation of VSS and to correlate the observed VSS with the concentration of biological scatterers.

The incoming surface solar radiation was measured by a continuously recording actinograph mounted on the port side of the icebreaker's bow. Concentrations of phosphate-P, silicate-Si, nitrate-N, nitrite-N, and ammonium-N were determined from water samples collected at depths corresponding to 100, 50, 10 and 1 percent of the surface illumination. The level of primary productivity was obtained by calculating the uptake of radioactive carbon using the liquid scintillation technique. Water samples from the four depths were incubated from local apparent noon to midnight (or sunset). The incubator was mounted next to the actinograph. The amount of chlorophyll pigments in the samples was determined following the procedure recommended by the Scientific Committee on Oceanic Research of the United Nations Educational, Scientific, and Cultural Organization. Zooplankton samples were obtained with a 3/4-m diameter closing net (mesh size 110 microns) that was towed vertically.

Measurements of the acoustic volume reverberation were made by using a 60-kHz and a 105-kHz pulsed, continuous wave, vertically directed sonar. Each transducer was attached to a cable and lowered about 2 m into the water. Measurements were normally made after locating the ice edge and making traverses through it.

Figure 1. Sampling area and location of stations (dots) in the Chukchi Sea, July 1974.



Several stations were chosen at 1.6, 3.2, 8, and 16 kilometers on either side of the ice edge boundary.

Preliminary Results

In general, low levels of primary productivity were noted, especially in the open water. Primary productivity was very high, over 3 grams carbon/m³/half day, at only two stations. One of these was in an area with a large sea-ice cover (over 7 oktas), and the other had a homogenous water column and was off the northeast Siberian coast, an area of divergence. The numerical value of the primary productivity index, the amount of carbon assimilated per amount of chlorophyll *a* per half day, varied from about 3 to 24.

Biological, chemical, and physical data were analyzed statistically for the magnitude of primary productivity variability and for the relative significance of different environmental variables to primary productivity. Based on these results, the following deductions were made:

1. Most of the observations were made subsequent to the phytoplankton bloom.

2. The phytoplankton was capable of using very low levels of solar radiation for photosynthesis; therefore, the available micronutrients were quickly used at all levels in the photic zone above the pycnocline. Also, because of strong density stratification in the water column, mainly from the melting of ice, the rate of replenishment of water from deeper, nutrient-rich layers was slow.

3. The photic zone always had phosphate-P in substantial quantities. Nitrate-N and ammonium-N showed large variability, with the coefficient of variability being 217 and 154 percent, respectively. The amount of silicate-Si was low; at times, it was about 2 milligrams-atom/m³, less than the threshold concentration for silicate limitation of algal photosynthesis.

4. The availability of inorganic nitrogen sources was retarded in the upper layers of the photic zone. Inorganic nitrogen was considered to be the limiting nutrient for algal photosyntheses, but the possibility of multiple nutrient limitation cannot be discounted.

5. There was a general subsurface accumulation of plankton algae. This accumulation was often associated with the pycnocline. Such a distribution could result from the sinking of unconsumed algae from the surface layers, indicating a rather inefficient use of phytoplankton by the herbivores, at least in the upper layers.

6. Zooplankton samples were analyzed for biomass (mg dry weight), relating to the phytoplankton productivity, and for their size-frequency distribution, relating to the VSS data. Zooplankton was examined for five size groups: less than 0.5 millimeter, 0.5 to 1 millimeter, 1 to 5 millimeters, 5 to 10 millimeters, and larger than 10 millimeters. Of these groups, the latter three were considered to be possibly related to the observed scattering of sound. Specimens in these size groups were dominated primarily by copepods (*Calanus glacialis*, in particular) and occasionally by young shrimp and pelagic snails. Large specimens generally belonged to the chaetognaths, appendicularians, and ctenophores. Only a few specimens of euphausiids were collected. The total zooplankton biomass showed large variability, ranging from about 1 to 64 mg/m³. Similarly the number of zooplankton was highly variable; in the 1 to 5 millimeter size group, the concentration varied from about 15 to 700 individuals/m³.

The acoustic data at 60 and 105 kHz (heterodyned down to 5 or 10 kHz) were recorded on magnetic tapes and analyzed by a digital averaging method developed at the laboratory. Estimates of the volume scattering strength of a cubic meter of water were obtained for several contiguous, but nonoverlapping layers at a depth interval of 5 m. The following features were observed:

1. Variations in the VSS at each depth interval were generally similar.

2. In most locations, VSS at 105 kHz was higher than at 60 kHz by several decibels.

3. High VSS values, about -60 dB at 105 kHz and -74 dB at 60 kHz, were frequently observed.

4. For several groups of stations averaging 16 km apart, the 60-kHz data showed little variability in the VSS in the upper 25 m.

Theoretical Calculations

Theoretical calculations of the scattering are an important link in establishing a relationship between the VSS at various frequencies and the concentrations of biological material sampled or predicted on the basis of the model. Measurements of the VSS and biological sampling data are not sufficient to predict interrelationships. A sound theoretical basis, verified by measurement under a variety of conditions, is needed to establish the predictive capability.

An approximate calculation treating the organisms as a distribution of spherical, fluid scatterers can be performed with relative ease. Previous work at the laboratory on the properties of acoustic lenses resulted in computer programs that calculated the acoustic field inside liquid or solid spheres excited by an incident plane or spherical wave in a liquid medium. These programs can be modified to calculate the scattered field and the differential scattering cross section as a function of frequency and the elastic parameters of the sphere. An expression for the target strength of a scatterer can be derived as a function of its size, density, compressibility, and the wavelength. This expression can be extended to obtain target strengths for various distribution patterns of the scatterers.

This theoretical basis will be integrated into the program, and the theoretical results, based on parameters obtained from the sampling data, will be compared with the measured scattering strength. The role, if any, that air bubbles play in the VSS results will be examined. The outcome of these efforts will be a guide for determining the parameters that should be given priority in future sampling programs.

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